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Digital signal processing is an ever increasingly important application of theoretical principles needed to process numerical information by digital means. DSP has recently been impacted by the technology of microelectronics (VLSI). VLSI has changed certain previously held concepts on the complexity of algorithms and implementations. This research has been directed at understanding the important parameters in VLSI as applied to digital signal processing problems.

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Final Report on Research Findings for Contract DAAG29-80-K-0062,

Efficient Realizations in Hardware Implementations

for Digital Signal Processing

Digital signal processing is an ever increasingly important application of theoretical principles needed to process numerical information by digital means. DSP has recently been impacted by the technology of microelectronics (VLSI). VLSI has changed certain previously held concepts on the complexity of algorithms and of implementations. This research has been directed at understanding the important parameters in VLSI as applied to digital signal processing problems.

In this research we use the terms **task** to mean the input/output description of a DSP problem, **algorithm** or **realization** to define the actual computation and **implementation** to mean the hardware definition of the algorithm.

Our research began by concentrating on two important tasks in DSP - spectral estimation and digital filtering. Spectral estimation algorithms are many and varied and so our first problem was to really examine the assumptions inherent in the various available algorithms. This resulted in research which investigated many different forms of spectral estimation. The thrust of this research was to come up with estimators that would be useful to implement in VLSI. One important class of nonparametric estimators is the so-called discrete Fourier transform generally implemented using the FFT. Dr. Masud Arjmand as part of his Ph.D. thesis [1] developed new structures for VLSI implementation of the DFT. These new structures possess many of the attributes needed for good VLSI implementation. These include:

(i) a modular and regular structure

(ii) reasonably good finite register effects

(iii) high data throughput

(iv) reasonably complexity as measured by the relative chip area consumed vis-a-vis other implementations.

Based on this research another Ph.D. student, Dr. Allan Steinhardt, investigated parametric spectral estimators. These parametric estimators offer the advantage of apparent high resolution **provided** the class of spectra under study can be adequately characterized a priori. In order to implement spectral estimators in VLSI it is useful to obtain a simple characterization or models of the spectra. Dr. Steinhardt first tried to use finite-state systems to model spectra. The idea was that since a finite-state system is inherently digital its implementation would be "natural" for VLSI. Unfortunately, this research led us to the conclusion that such a characterization is not simple because it requires an enormous number of states. This blind alley was then replaced by an investigation of various parametric spectral estimators in the hope of consolidating many estimators into a single theoretical structure which then could be used as the basis for a VLSI implementation. This work resulted in the Ph.D. thesis [2] of Allan Steinhardt. It is more theoretical than the work of Arjmand but does serve to consolidate a great deal of parametric spectral estimation. What is needed at this point is further research to obtain VLSI implementations of these theoretical models.

In parallel with this research on spectral estimation algorithms was research carried out by Dr. Denis Henrot [3] on structures for digital filtering that could be efficiently implemented in VLSI. The digital filtering problem is easier to attack than the spectral estimation problem because the input/output task is better defined. Spectral estimation has many algorithms dependent on the class of spectra to be estimated. Digital filtering consists of a single well-defined input/output task. Dr. Henrot was able to obtain what we consider to be an excellent structure for VLSI implementation. It is highly modular and regular, has good finite register effects, good data throughput, and is of reasonable complexity.

This research has resulted in several publications which are listed below, and three Ph.D. theses also included below.

[1] "Efficient Structures and Algorithms for Digital Signal Processing," Ph.D. Thesis, University of Colorado, 1981, by Masud Arjmand.

[2] "An Optimization Theroretic Framework for Spectral Estimation," Ph.D. Thesis, University of Colorado, 1983, by Allan Steinhardt.

[3] "On Modularity and Computational Parallelism in Digital Filter Implementations," Ph.D. Thesis, University of Colorado, 1983, by Denis Henrot.

[4] "Multifactor Algorithms for Noncyclic Digital Convolution," *Inter. Conf. on Acoustics, Speech, and Signal Processing,* Atlanta, Georgia, 1981.

[5] "A Comparison of Spectral Estimators for Real Data," *Inter. Conf. on Acoustics, Speech, and Signal Processing,* Atlanta, Georgia, 1981.

[6] "Digital Signal Processing Structures for VLSI," invited paper to the *International Conference on Digital Signal Processing,* Florence, Italy, 1981.

[7] "Efficient Realizations for Digital Processing for VLSI," invited tutorial paper for an NSF sponsored workshop on DSP for scientists and engineers in the U.S.A. and Italy, August 1981, Portovenere, Italy.

[8] "A New Algorithm and Implementation of the DFT," invited paper for the *IFAC Symposium on Theory and Applications of Digital Control,* January 1982.

[9] "Low Roundoff Noise and Normal Realizations of Fixed Point IIR Digital Filters," W. L. Mills, C. T. Mullis, R. A. Roberts, *IEEE Trans. on Acoustics Speech and Signal Processing,* vol. ASSP-29, pp. 893-903, August 1981.

[10] "A Multifactor DFT Algorithm and Implementation," M. Arjmand and R. A. Roberts, *The Proceedings of the Fifteenth Asilomar Conference on Circuits,* Systems, and Computers, November 1981.

[11] "Power Spectral Estimation Using ARMA Models," R. A. Roberts and C. T. Mullis, *Proceedings of the Institute of Acoustics, Spectral Analysis and its Use in Underwater Acoustics,* Imperial College, London, 29-30, April 1982.

[12] "A Multifactor Algorithm for Two-Dimensional Convolution," A. I. ElFallah and R. A. Roberts, *Proceedings of the IEEE Institute Conference on Acoustics, Speech, and* Signal Processing, Paris, May 1982.

[13] "Block Processing Structures for Fixed Point Digital Filtering," C. A. Wambergue and R. A. Roberts, *Proceedings of the IEEE Institute Conference on Acoustics, Speech, and Signal Processing,* Paris, May 1982.

[14] "An Interpretation of Error Spectrum Shaping in Digital Filters," C. T. Mullis and R. A. Roberts, *IEEE Trans. on Acoustics, Speech, and Signal Processing,* vol. ASSP-30, No. 6, December 1982, pp. 1013-1016.

[15] "An Optimization Theoretic Framework for Spectral Estimation," A. Steinhardt and R. A. Roberts, *Proceedings of ICASSP83,* Boston, May 1983.

[16] "A Modular and Orthogonal Digital Filter Structure for Parallel Processing," D. Henrot and C. T. Mullis, *Proceedings of ICASSP83, Boston, May 1983.*

Invited Presentations on Digital Processing Realization for VLSI

a. R. A. Roberts, Spain Workshop on Digital Signal Processing with special emphasis on VLSI. Barcelona, Spain, September 1983.

b. R. A. Roberts, L'Aquila Workshop on Digital Signal Processing, L'Aquila, Italy, September 1983.

c. R. A. Roberts, California Institute of Technology, Pasadena, California, November 1983.

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